Maintaining Adequate Carbon Dioxide Washout for an Advanced Extravehicular Mobility Unit

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Over the past several years, NASA has realized tremendous progress in technololgy development that is aimed at the production of an Advanced Extravehicular Mobility Unit (AEMU). Of the many functions provided by the spacesuit and portable life support subsystem within the AEMU, delivering breathing gas to the astronaut along with removing the carbon dioxide (CO_2) remains one of the most important environmental functions that the AEMU can control. Carbon dioxide washout is the capability of the ventilation flow in the spacesuit helmet to provide low concentrations of CO_2 to the crew member to meet breathing requirements. CO_2 washout performance is a critical parameter needed to ensure proper and sufficient designs in a spacesuit and in vehicle applications such as sleep stations and hygiene compartments. Human testing to fully evaluate and validate CO_2 washout performance is necessary but also expensive due to the levied safety requirements. Moreover, correlation of math models becomes challenging because of human variability and movement. To supplement human CO_2 washout testing, a breathing capability will be integrated into a suited manikin test apparatus to provide a safe, lower cost, stable, easily modeled alternative to human testing. Additionally, this configuration provides NASA Johnson Space Center (JSC) the capability to evaluate CO_2 washout under off-nominal conditions that would otherwise be unsafe for human testing or difficult due to fatigue of a test subject. Testing has been under way in-house at JSC and analysis has been initiated to evaluate whether the technology provides sufficient performance in ensuring that the CO_2 is removed sufficiently and the ventilation flow is adequate for maintaining CO_2 washout in the AEMU spacesuit helmet of the crew member during an extravehicular activity. This paper will review recent CO_2 washout testing and analysis activities, testing planned in-house with a spacesuit simulator, and the associated analytical work along with insights from the medical aspect on the testing.

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Nomenclature

ACFM	=	actual cubic feet per minute
AEMU	=	Advanced Extravehicular Mobility Unit
BTU	=	British Thermal Units
CEM	=	controlled evaporation mixer
CFD	=	computational fluid dynamics
COMCAP	=	communication cap
CO_2	=	carbon dioxide
EMU	=	Extravehicular Mobility Unit
EVA	=	extravehicular activity
Hg	=	Mercury
H_2O	=	water
hr	=	hour
ISS	=	International Space Station
JSC	=	Johnson Space Center
mmHg	=	millimeters of mercury
mph	=	miles per hour
NIOSH	=	National Institute for Occupational Safety and Health
N_2	=	nitrogen
OSHA	=	Occupational Safety and Health Administration
O_2	=	oxygen
PLSS	=	portable life dupport dubsystem
RCA	=	Rapid Cycle Amine
SMAC	=	Spacecraft Maximum Allowable Concentrations
SMTA	=	suited manikin test apparatus
SSAS	=	space suit assembly simulator
VDA	=	ventilation duct assembly

I. Introduction

Spacesuits are unique. They are used to survive astronauts in space. Performing extravehicular activities (EVAs), otherwise referred to as spacewalks, continue to be one of the most critical components of human space flight. Because EVAs are performed at vacuum, they present technological challenges that are unique for providing a safe haven for the spacewalker. The spacesuits have to be pressurized; therefore, critical environmental control functions have to be sustained over the course of a spacewalk. Of the many functions that the spacesuit provides, delivering breathing gas to the astronaut along with removing the carbon dioxide (CO_2) remains one of the most important environmental functions that a spacesuit can control. Other functions include maintaining core body temperature, along with providing mobility to perform required tasks, communications, biomedical data, environment protection, and waste management.

The EVA portable life support subsystem (PLSS) provides a critical function supporting the Advanced Extravehicular Mobility Unit (AEMU) project. The ventilation loop within the PLSS in the spacesuit is important because it is the primary way to transport and provide conditioned oxygen (O_2) to the suit for the purpose of pressurization and astronaut breathing. The CO_2 is removed, and humidity and trace contaminants are controlled. The flow of O_2 must be adequate enough to wash out CO_2 in the helmet and to prevent fogging in the helmet.

Human testing is being performed at NASA Johnson Space Center (JSC) to quantify and evaluate CO_2 washout performance within the spacesuit helmet. The CO_2 washout performance must be adequate to safely deliver proper breathing gas to the crew member. Improvements in CO_2 washout efficiencies have the potential benefits of providing adequate washout at lower flow rates, which can reduce fan requirements and power. Additionally, such improvements can reduce CO_2 removal efficiency requirements imposed on the Rapid Cycle Amine (RCA), which is the technology assembly in the PLSS responsible for removing CO_2 and humidity generated by the suited crew member.

A suited manikin test apparatus (SMTA) is being developed at JSC to supplement human testing activities. The SMTA will contain a breathing manikin apparatus that will characterize and assess the CO_2 concentrations within the space suit assembly simulator (SSAS) to develop an understanding of the effects on the internal ventilation environment.

This paper summarizes the implications of CO_2 concentration, system integration approach to CO_2 washout, SMTA and human vent duct testing activities taking place at JSC, and computational fluid dynamics (CFD) analysis and correlation activities associated with the CO_2 washout testing.

II. Implications of Carbon Dioxide Concentration

A. Medical Implications

The CO_2 concentration in the spacesuit is critical to manage. The question is to what degree. Several entities currently control the CO_2 concentration limits for safe human operations in industry. The entity that controls the concentration limits for CO_2 in industry is the Occupational Safety and Health Administration (OSHA).[1] The National Institute for Occupational Safety and Health (NIOSH) is an organization that researches and advises the OSHA on occupational limits for harmful substances.[2] NASA, on the other hand, is well aware of the limits set by OSHA and advisories made by NIOSH. However, NASA has published its own limits for space applications known as the Spacecraft Maximum Allowable Concentrations (SMAC) values.[3] Additionally, NASA has set more stringent Flight Rules for the International Space Station (ISS) and EVA operations due to their unique operations in the space environments.[4]

Recent research by Law et al. suggests that it may be sufficient to set more stringent criteria for CO_2 levels for exposure limits than is currently set by the ISS operations due to certain crew symptoms data.[5] Headache and lethargy have been reported as symptoms and are being investigated. However, it is still unclear whether CO_2 sensitivity is increased by exposure to microgravity. Additionally, it has not been ruled out that certain individuals may be more susceptible to the effects of CO_2 than others and that the adaptation to microgravity may potentiate the effects of CO_2. Considering all these factors, the AEMU team has chosen the more stringent criteria of maintaining the average inhaled CO_2 level to 3.8 millimeters of mercury (mmHg) as the challenging target for CO_2 control development and testing efforts. As well, the team is committed to working closely with the NASA toxicologist to keep abreast of the latest research in CO_2 limits.

B. Resource Implications

Accumulation of CO_2 in a closed environment of the spacesuit can cause incapacitation and ultimately loss of life without some type of life support. Additionally, CO_2 removal requires energy and resources in a spacecraft as well as in a spacesuit. It is reasonable to conclude that increased CO_2 removal requires an increase in resources used and increased logistics to maintain necessary resources on the ISS and in a spacesuit. Therefore, a balance between adequate CO_2 levels to maintain a crew member's health and CO_2 levels that are operationally feasible for both the ISS and spacesuit is necessary.[6]

III. Systems Integration Approach to Carbon Dioxide Washout

Maintaining CO_2 levels within the AEMU that are sufficiently comfortable for the crew member and avoid any or all symptoms of hypercapnia is critical. Therefore, it becomes a systems challenge to overcome this potentially hazardous condition. Multiple techniques and designs have the potential to overt this severe condition in the new AEMU. These techniques and designs will have to be integrated in an effectual systematic way to meet the stringent CO_2 levels in the AEMU.

The overall system approach involves all the components in the ventilation loop of the PLSS and the human-in-the-loop in the AEMU spacesuit. More specifically, the CO_2 levels inhaled by a crew member in the spacesuit are dependent upon multiple parameters and design features in the spacesuit. The features cause variability in the spacesuit and, without appropriate system integration, could be lethal. The parameters and design features are as follows:

1. The helmet design
2. The ventilation duct design in the helmet
3. The volumetric flow rate in the ventilation loop as defined by the fan design
4. The metabolic rate of the crew member
5. The breathing pattern of the crew member
6. The mouth and nose flow split patterns of the crew member
7. The head shape and hair combination of the crew member
8. The head orientation of the crew member
8. The design of the communication cap (COMCAP)
9. The concentration of CO_2 introduced into the helmet

The inlet concentration of CO_2 into the helmet is a direct correlation to the outlet concentration of the RCA. Therefore, maintaining the necessary concentrations of CO_2 at the helmet inlet may require several system tradeoffs with the RCA and other suit design features mentioned previously. Recent suited human testing and CFD efforts have indicated that relatively small changes in head position and helmet inlet ducting configurations might significantly affect inspired CO_2 levels, potentially leading to CO_2 toxicity impacts on the suited crew member. However, no trials have been accomplished to assess the system impact of the actual RCA in combinations with these other design features. It is imperative that a system assessment via testing be performed to seek out impacts associated with the RCA and the other parameters mentioned above. It is conceivable that with a properly designed helmet flow inlet design in combination with a properly designed RCA, there could be increased CO_2 washout effectiveness. Other system benefits could be seen in the size of the PLSS battery due to reduced fan power demands and mass impacts on the O_2 tanks due to ullage losses associated with the cycling of the RCA.

IV. Carbon Dioxide Washout Testing

A. Prior Carbon Dioxide Washout Evaluations

CFD analyses supporting AEMU development efforts have been previously performed to determine CO_2 washout effectiveness in a spacesuit environment.[7,8] The amount of CO_2 inhaled depends on the concentration of CO_2 at the inlet, the amount of volumetric flow, flow inlet design, helmet design, metabolic rate, simulated breathing pattern, and head shape/orientation.

Historically, emphasis has been placed on inlet CO_2 concentration, metabolic rate, and volumetric flow. Recently, work has been conducted on inlet configuration design. Analysis results show that certain inlet configurations can induce more mixing than others, which increases the amount of CO_2 inhaled. Flow inlet direction and/or velocity magnitude contribute to this trend.

B. Suited Manikin Test Apparatus Testing Activities

The SMTA will be used to perform CO_2 washout characterization of several ventilation duct configurations, metabolic conditions, and ventilation loop flow rates. Total gas pressure within the SMTA will also be varied. The SMTA will be initially tested in the Ventilation Laboratory and will be subsequently tested in a configuration merged with the PLSS 2.0 test article in the PLSS 2.0 Laboratory.[9]

1) Test Configurations

   i) PLSS Ventilation Laboratory SMTA Testing (Integrated Test Sequence (ITS) 1.0)

      The ITS 1.0 of SMTA testing will be performed with the SMTA integrated with the preexisting JSC PLSS Ventilation Laboratory (JSC Building 7, room 2006) integrated ventilation subsystem test loop. The integrated ventilation subsystem test loop was designed to accommodate the SMTA test with the required instrumentation, as shown in Fig. 1. The test loop will maintain the desired simulated metabolic rate, flow rate, and system pressure to interface with the SMTA. Also as shown in Fig. 1, the integrated ventilation test loop will interface to facility nitrogen (N_2) and facility CO_2 via the Gas Console (stationary laboratory gas supply). The facility N_2 will supply the test loop with dry N_2 and will provide any ullage lost from the RCA valve actuation. The facility CO_2 will supply the controlled evaporation mixer (CEM) unit with the required simulated human metabolic load (i.e., CO_2 and water (H_2O)).

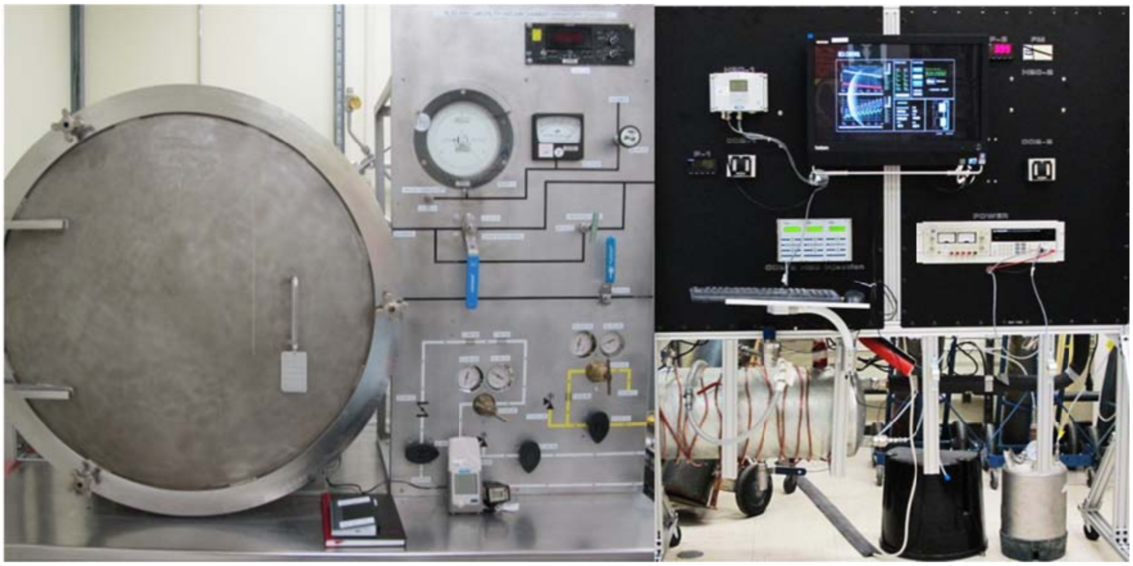

Figure 1. Utility vacuum chamber far (left), gas console (middle), and ventilation test loop (right).

The breathing system of the SMTA will mix the CO_2 and H_2O vapor mixture exiting the CEM with dry N_2 to create a characteristic breathing profile, ported orally on the manikin. The simulated exhale breath of the manikin is controlled by two mass flow controllers and one solenoid valve. All three components work together to supply the humidified CO_2 gaseous stream to the manikin. The simulated inhale breath is controlled by one mass flow controller and one solenoid valve. Each set of mass flow controllers and solenoid valves will alternate to simulate a breathing test subject.

A Triscroll® vacuum pump connected to the ventilation test loop will draw the system pressure down to the desired operating pressure for all test cases. A back pressure regulator will control the system pressure at all times. The utility vacuum chamber as shown in Fig. 1 will be connected to the RCA vacuum port to represent the space vacuum that is required to desorb CO_2 and H_2O vapor from the amine packed beds in the RCA. The test schematic for the PLSS Ventilation Laboratory SMTA Testing is shown in Fig. 2.

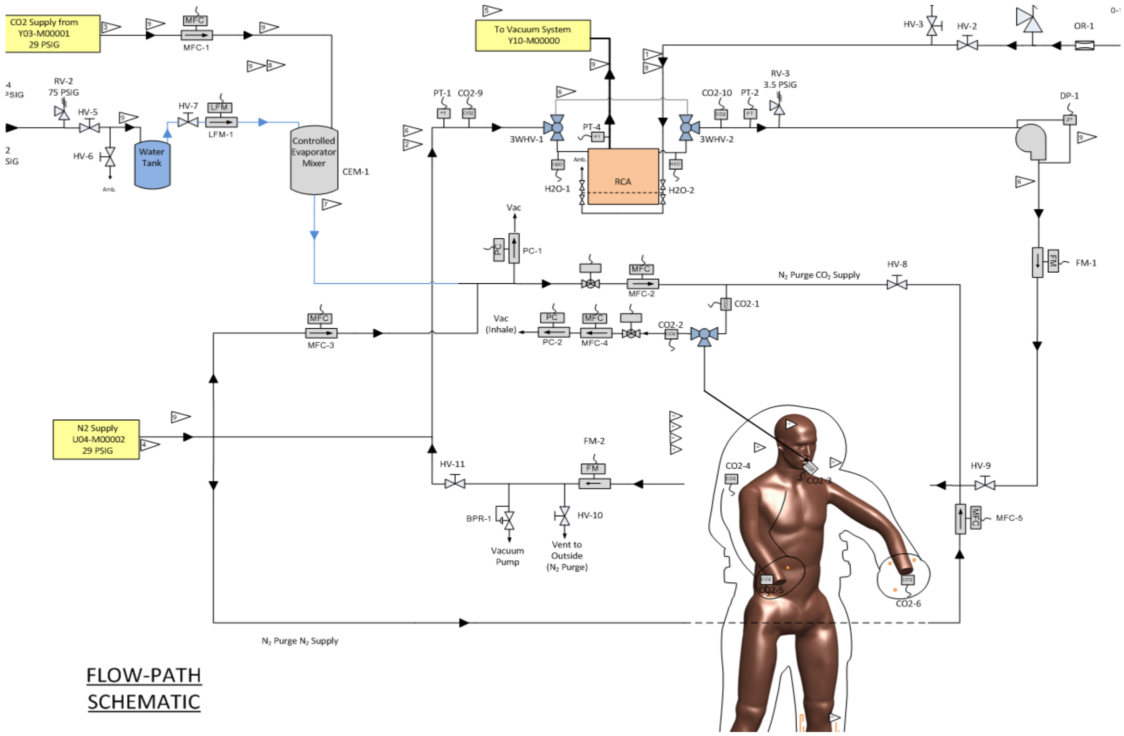

Figure 2. PLSS Ventilation Laboratory SMTA test schematic.

ii) PLSS 2.0 Laboratory SMTA Testing (ITS 2.0)

For the ITS 2.0, the SMTA will be integrated with the PLSS 2.0 test facility (JSC Building 7, room 2005) to test CO_2 washout performance similar to the testing performed in the SMTA PLSS Ventilation Laboratory test sequence. RCA 1.0 (older unit) will be used in the PLSS Ventilation Laboratory test sequence, and RCA 2.0 (newer unit) will be the unit integrated into the SMTA PLSS 2.0 test sequence. The results of this testing will include any performance changes caused by the differences in the two RCA units.

The PLSS 2.0 Laboratory SMTA CO_2 washout testing will seek to quantify the CO_2 concentration levels within a simulated spacesuit environment with the SMTA interfaced to the PLSS 2.0. PLSS 2.0 is a high-fidelity mock-up of the advanced PLSS and will provide more accurate CO_2 concentration levels than those obtained in ITS 1.0.

The objectives of the PLSS 2.0 Laboratory SMTA CO_2 washout test are as follows:

1) to assess the uniformity of mixing within the SMTA;
2) to validate CFD model predictions; and
3) to evaluate various helmet ventilation duct configurations.

Each SMTA test scenario test will characterize and assess the CO_2 concentrations within the SMTA to develop an understanding of the effects on the internal environment. The SMTA test design will capture the necessary parameters to enhance the validity and accuracy of the SMTA test and testing models. Testing will be performed at various CO_2 concentrations and at various pressures to assess the effect of these parameters. The test schematic for the PLSS 2.0 Laboratory SMTA Testing is shown in Fig. 3.

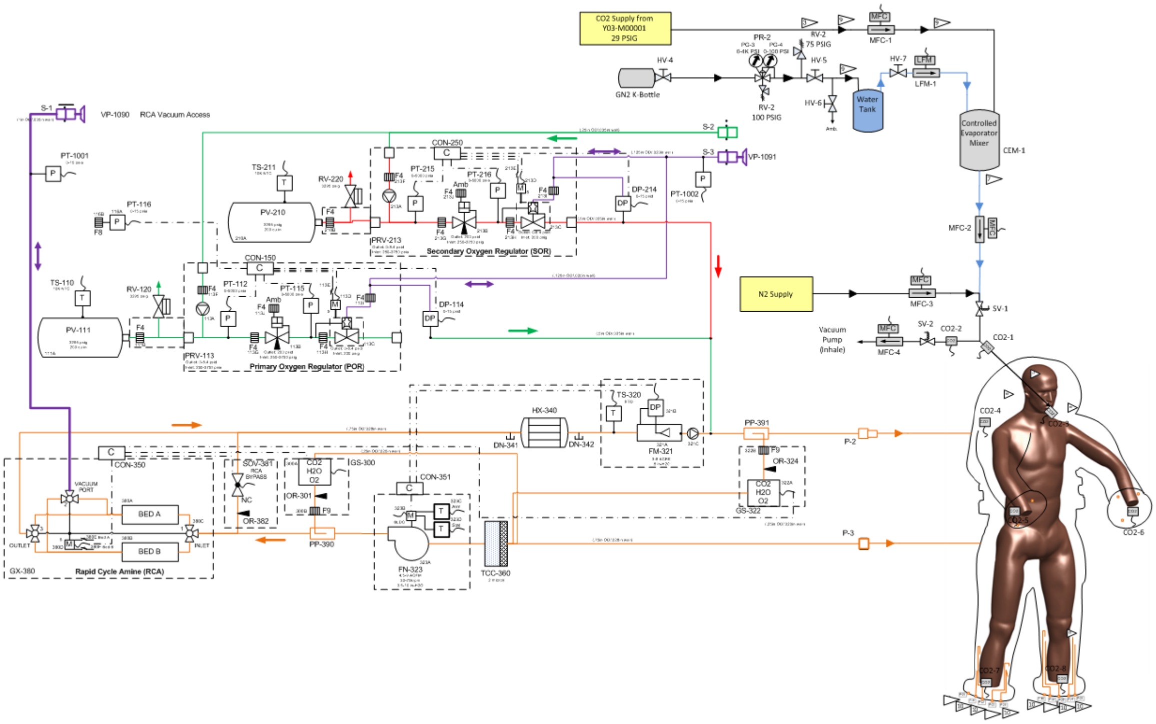

Figure 3. PLSS 2.0 Laboratory SMTA test schematic.

2) Components

The following is a list of major components that will be used in the PLSS Ventilation Laboratory SMTA Testing (ITS 1.0) and the PLSS 2.0 Laboratory SMTA testing (ITS 2.0). A descripton of each major item is provided and a picture of several items is also included. The components reviewed include the SSAS, SMTA, RCA, ventilation duct assembly (VDA), human metabolic gas simulator, and test sensors.[9,10]

i) SSAS

The SSAS was designed and manufactured to emulate a Mark III spacesuit design. The Mark III was scanned and digitally converted to a Pro E design. The Pro E design, as shown in Fig. 4, was sent to Solid Concepts of Poway, CA, to fabricate the suit into a urethane see-through hard frame that emulates a suit and to be known as the SSAS. Also, it was designed so as to accommodate a manikin in the suit as well. The SSAS is shown in Fig. 5.[10]

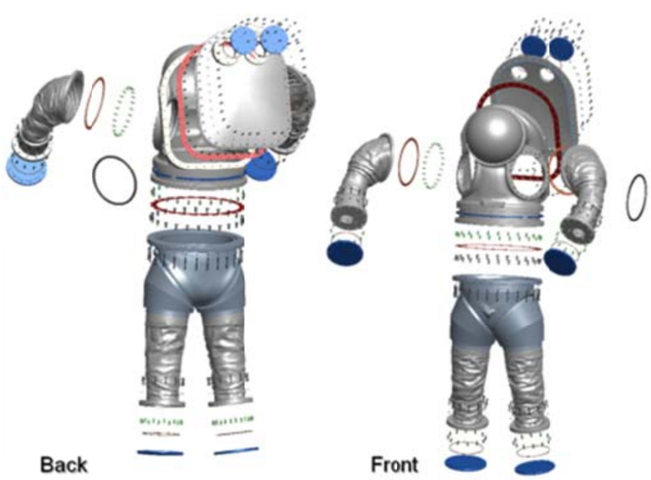

Figure 4. SSAS design.

Figure 5. SSAS.

ii) SMTA

The SMTA design will consist of installing a modified commercial off-the-shelf manikin into the SSAS as shown in Fig. 6. The modified manikin will be designed to include breathing capability that simulates breathing profiles with CO_2 and H_2O, metabolic gas consumption, and variation with metabolic rate.[9]

The SMTA will provide the capability to perform CO_2 washout testing while integrated into the existing PLSS ventilation loop test stand located in the PLSS Ventilation Laboratory (room 2006 of building 7) at JSC (ITS 1.0). The SMTA will be also be capable of being integrated with PLSS 2.0 to perform the CO_2 washout testing for the PLSS 2.0 Laboratory SMTA Test (room 2005 of building 7) at JSC (ITS 2.0).[9]

Figure 6. SMTA model (left) and actual in SSAS (right).

iii) RCA

The RCA is a component that is specifically designed for the AEMU ventilation loop to remove CO_2 and humidity generated by the crew member within the spacesuit.[11,12] The RCA is a new technology currently under development by NASA with United Technologies Corporation Aerospace Systems and funded by the NASA Office of Chief Technologist.[13] The RCA is a low power assembly capable of simultaneously removing CO_2 and humidity from a ventilation loop and subsequent regeneration when exposed to a vacuum source.[14] The RCA assembly is configured with two solid amine sorbent beds.[15,16] The design goal is for the beds to alternate between an uptake mode and a regeneration mode resulting in the ability to cycle continuously to achieve CO_2 and humidity removal for up to 100 EVAs. During the uptake mode, the sorbent in one bed (Bed A) is exposed to the breathing gas flowing in the AEMU ventilation loop to adsorb CO_2 and humidity. At the same time during the regeneration mode, the sorbent in the alternate bed (Bed B) is exposed to a vacuum source and desorbs CO_2 and humidity.[17,18,19] The RCA also employs a novel valve assembly that allows for an efficient simultaneous bed operation. The valve assembly is also designed to minimize O_2 loss to the vacuum source during actuation. Additionally, a compact low-powered integrated controller is configured to control the RCA assembly through its modes of operation in the AEMU ventilation loop. The RCA technology has been matured over the last several years. The initial development unit is RCA 1.0 and the second generation unit is RCA 2.0. RCA 2.0 employs a higher fidelity valving structure to shift between amine beds more efficiently and reliabily.[20] The RCA 1.0 will be used for the PLSS Ventilation Laboratory SMTA Test (ITS 1.0). RCA 2.0 will be used for the the PLSS 2.0 Laboratory SMTA Test (ITS 2.0). RCA 1.0 is shown in Fig. 7; RCA 2.0 is shown in Fig. 8.

Figure 7. RCA 1.0.

Figure 8. RCA 2.0.

iv) VDA

A spacesuit helmet developmental VDA was specifically designed for ground testing to improve and verify CFD models. This test-specific hardware will also be used to determine which of the defined airflow configurations produce the greatest CO_2 washout in the oral nasal region. The developmental VDA consists of five vents positioned along the neck ring of a development spacesuit as shown in Fig. 8. This VDA will be attached to the Hard Upper Torso near the neck ring of both the SMTA and the Mark-III spacesuit. Each of the vent openings will be routed to a manifold located on the rear hatch of the SMTA and Mark-III. These valves, located on the exterior of the suit hatch, will be easily reconfigurable to allow ventilation in each VDA port to be turned on or off. Various flow configurations are possible with the VDA test hardware design in Fig. 9.[10]

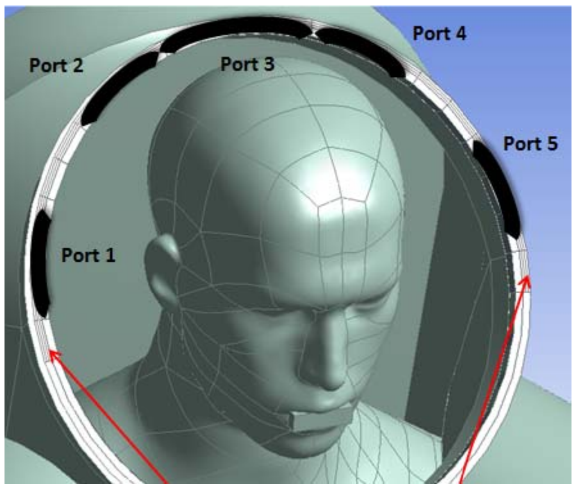

Figure 9. Developmental VDA port design.

v) Human Metabolic Gas Simulator

The facility CO_2 will supply the CEM unit with the required simulated metabolic load (i.e., CO_2 and H_2O) as shown in Fig. 10. The CEM system is an advanced liquid delivery system that can be applied for atmospheric or vacuum processes to simulate human metabolic flow (Bronkhorst High-Tech B.V.). The vapor generation system consists of a liquid flow meter, a mass flow controller for a carrier gas, and a temperature-controlled mixing and evaporation device. The CO_2 flow rate will be controlled using a mass flow controller and will then be directed into the CEM where the CO_2 will be heated and mixed with the water injection. The water injection rate will be controlled with a LIQUI-FLOW flow meter upstream of the CEM to allow for precise water injection rates to be attained. A temperature-controlled heat exchanger designed within the CEM system adds heat to the mixture to ensure complete H_2O vaporization.[9]

Figure 10. CEM schematic and flow controllers.

vi) Test Sensors

Two CO_2 sensors will be installed in the inhale and exhale lines to monitor and record the CO_2 levels. A CO_2 sensor will be installed in the nasal area of the manikin to monitor and record the expected exhaled CO_2 concentration levels. Six CO_2 sensors will be installed internal to the SMTA and external to the manikin to monitor and record CO_2 levels at various locations. Mass flow meters will provide flow rate monitoring and control for the CO_2 and humidity injection rates, flow rate information on the ventilation loop, and will also provide flow rate information on the sinusoidal breathing pattern of the CO_2, H_2O, and N_2 mixture. Pressure and temperature sensors will also be present within the SSAS and the ventilation loop to aid in posttest mass balance calculations.[9]

C. Human Testing of Helmet Ducting Configurations

To validate the oronasal CO_2 washout data with the VDA configurations shown in Fig. 9, a subset of corresponding test conditions will be accomplished using a set of human testing activities. These test points will be acquired using the current CO_2 washout protocol, which has been shown to accurately record oronasal CO_2 levels in various developmental spacesuits.[10]

1) Test Configuration

Test subjects representing the range of sizes that fit in a developmental EVA spacesuit will be selected from the available pool of fitchecked and approved suit test candidates. Three test subjects will be used, with each subject performing the test twice to allow for data comparison between tests for consistency. Suit pressure will be maintained at 4.3 psi for each test run. Test subjects will wear the suit while resting in the donning stand, and while walking on a treadmill at varying speeds to generate metabolic rates (workloads) from approximately 500 to 3000 British Thermal Units (BTU)/hour (hr). Supply airflow will be varied at each workload from 6 actual cubic feet per minute (ACFM) (standard air flow rate) to a low of 4 ACFM, as long as helmet CO_2 levels remain acceptable. The schematic for the test configuration is shown Fig. 10.[10]

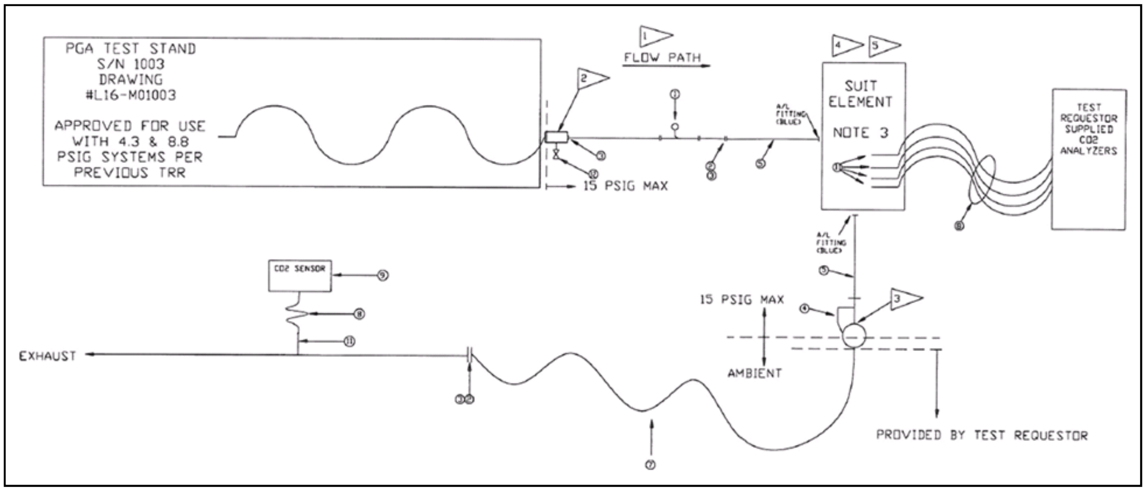

Figure 11. VDA human test configuration.

Oronasal CO_2 levels will be taken for each of the six VDA configurations for certain workload and airflow set points. Oronasal CO_2 levels and trending in the helmet will be monitored real-time via a gas analyzer with two sampling tubes positioned in the subject's oronasal area. Two additional sampling tubes (connected to a separate gas analyzer) will be placed in fixed locations in the helmet to simultaneously collect additional CO_2 data that will be used for CFD air flow model validation. The location of these four sensors is shown in Fig. 12.[10] Previous human-in-the-loop CO_2 washout testing had only included a single fixed sensor in the helmet. A second fixed sensor will be added to provide more data points to help validate the CFD models.

Metabolic rate will be calculated in real-time from the total CO_2 production as measured by another gas analyzer at the air outlet from the suit. The real-time metabolic rate will be used to monitor and adjust the treadmill speed to meet the target metabolic rates. Heart rate will also be monitored to ensure that the suited subjects stay within a safe exertion level.

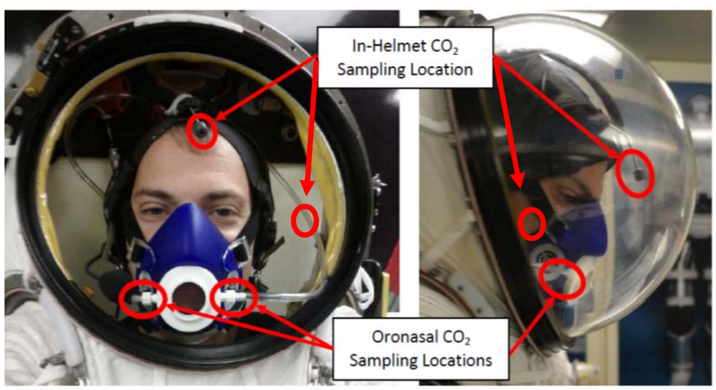

Figure 12: CO_2 sampling locations.

2) Components

i) Mark III Suit

The Mark III suit shown in Fig. 13 represents a rear-entry hybrid spacesuit configuration that is composed of hard elements such as a hard upper torso and hard brief section, and of soft components such as the fabric elbows and knees. The Mark-III suit hardware and ancillary support equipment provide the necessary functions and interfaces to conduct manned pressurized suit operations when combined with a suitable gas supply system, a cooling water supply, and a suitable communication system.[10]

Figure 13. Mark-III suit overview.

ii) Treadmill

The Mark-III suit is designed to allow walking while pressurized and is therefore suitable for treadmill use. Based on previous suited treadmill testing, only very low speeds will be needed to generate the desired metabolic rates. A Challenger 5.0 treadmill, shown in Fig. 14, will be used for this test. It is a standard treadmill with a running deck 20 inches in width by 58 inches in length. The treadmill can be operated via push-button controls at speeds from 0.1 to 10 miles per hour (mph) in 0.1 mph increments, as well as incline up to 25 degrees. Handrails are located at the front. These handrails extend back behind the user at an angle and incline with the running surface, although the incline feature will not be used during this test.[10]

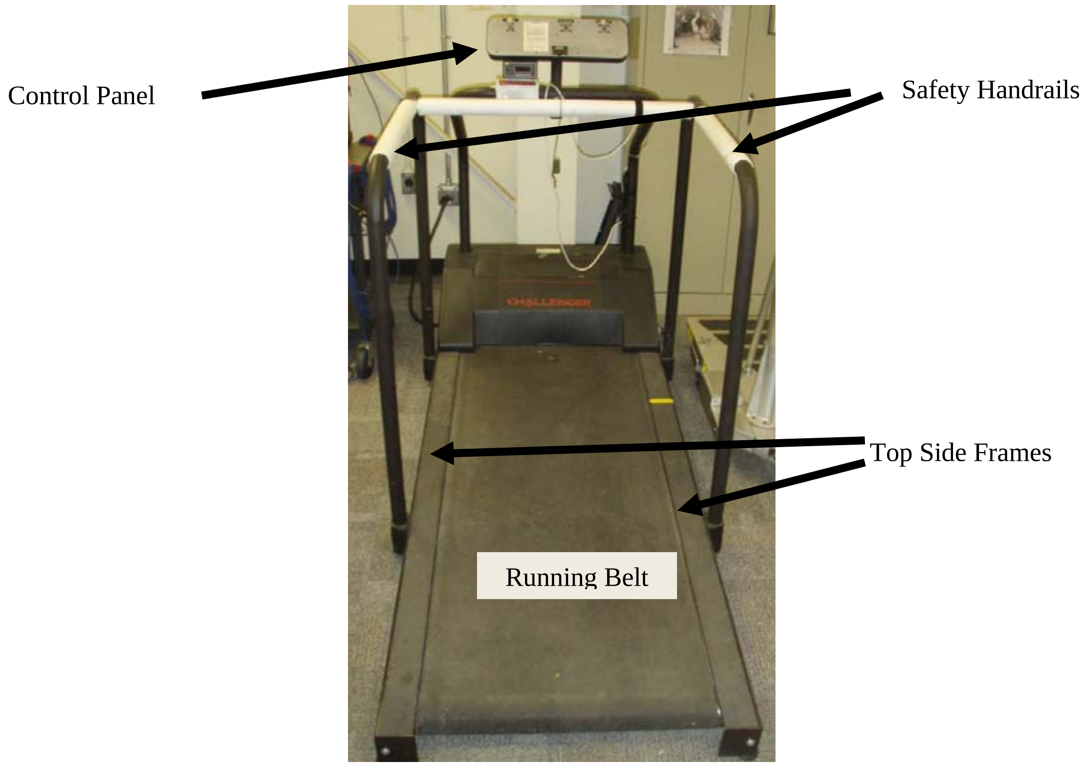

Figure 14. Challenger 5.0 treadmill.

V. Analytical Approach to Carbon Dioxide Washout

Transient CFD simulations are being performed to evaluate CO_2 washout performance within the helmet of the spacesuit. These efforts build upon prior CFD modeling efforts.[7, 8] ANSYS® Fluent is being used to model the geometry of the Mark-III and Z1 spacesuits to evaluate the ventilation flow characteristics specifically in the helmet and upper torso regions of the spacesuit. The manikin being used in the SMTP was laser scanned and a three-dimensional model was developed and imported into the CFD model.

A. Breathing Simulation with Computational Fluid Dynamics

The breathing of the simulated crew member is performed with user logic that interacts real-time with the CFD model simulation. The tracking of the different species across the mouth and nose domain surfaces is also performed with user logic, as is the simulated metabolic removal of O_2 and the production of CO_2 and H_2O vapor. In addition, the velocity-weighted average calculation of the inhale CO_2 value is performed with user logic during each timestep of the simulation to avoid complex post processing to determine the average CO_2 levels. The average CO_2 concentration experienced during the inhale cycle is ultimately compared to the breathing requirements to evaluate CO_2 washout performance. The same equations and logic used for the CFD simulations to calculate exhale concentrations based on inhale conditions are also being used to control the SMTP hardware to produce appropriate exhale conditions based on measured inhale concentrations and flow rates. The mass balance process for breathing cycles is shown in Fig. 15 and the breathing patterns used for various metabolic rates are shown in Fig. 16.

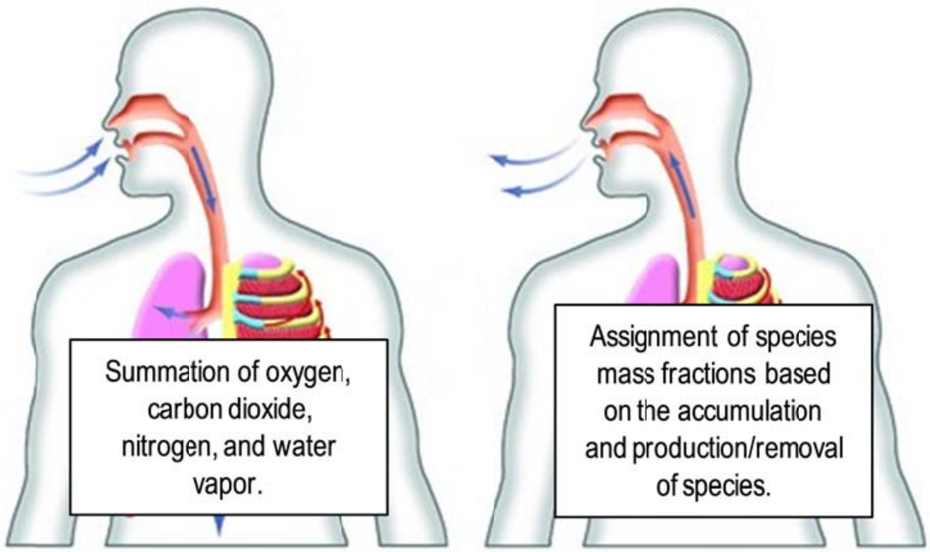

Figure 15. Breathing assessment with CFD model.

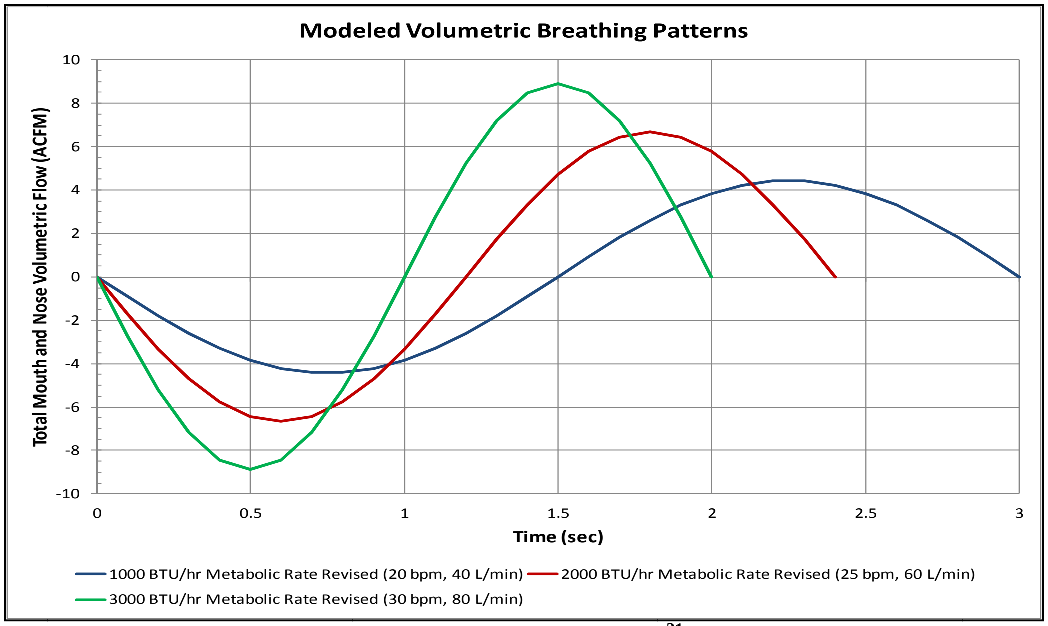

Figure 16. Breathing patterns assumed for CFD modeling.[21]

B. Recent Z1 Suit Computational Fluid Dynamics Evaluation

A CFD analysis was performed to compare Z1 suit CO_2 washout model prediction capability with available Z1 test data. The following assumptions were made for the case matrix.

- Metabolic rates: 1000, 2000, & 3000 BTU/hr
- Operating pressure: 19 psia
- Ventilation flow rates: 4, 5, & 6 ACFM

The inlet ventilation gas stream was composed of O_2 and N_2 (no H_2O vapor or CO_2). The ventilation duct configuration supplying the airflow is shown in the Fig. 17. The ventilation flow exit (outlet port) is located next to inlet ventilation duct in the Z1 suit as shown in Fig. 18.

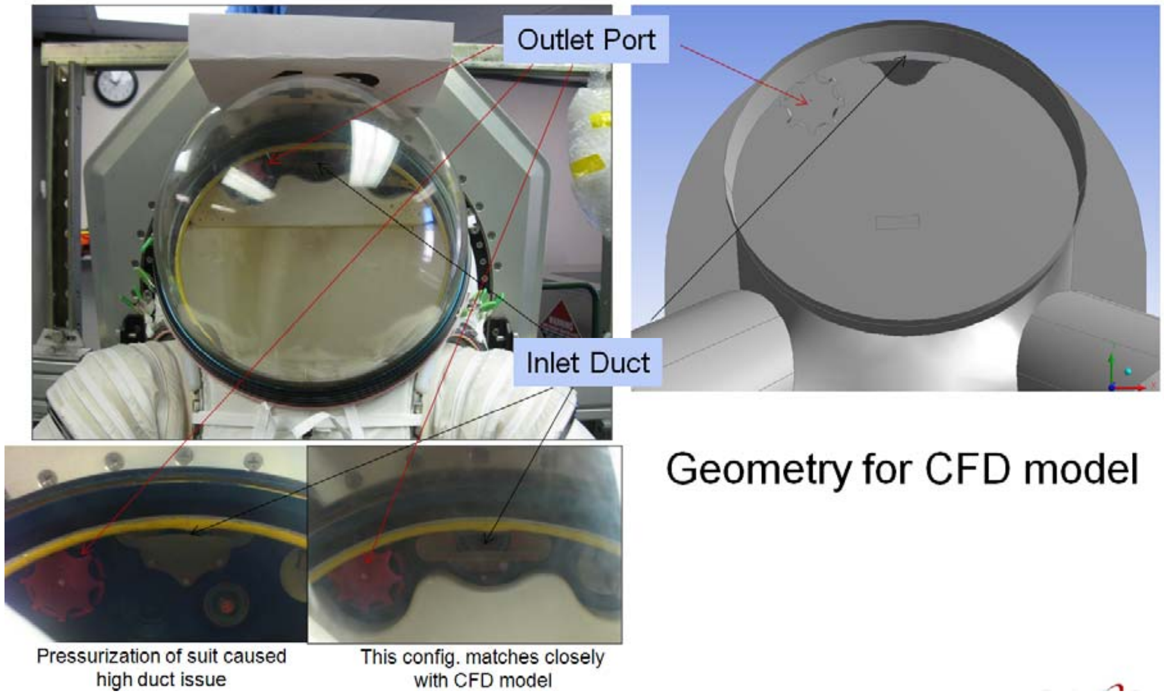

Figure 17. Z1 suit actual and modeled duct configurations.

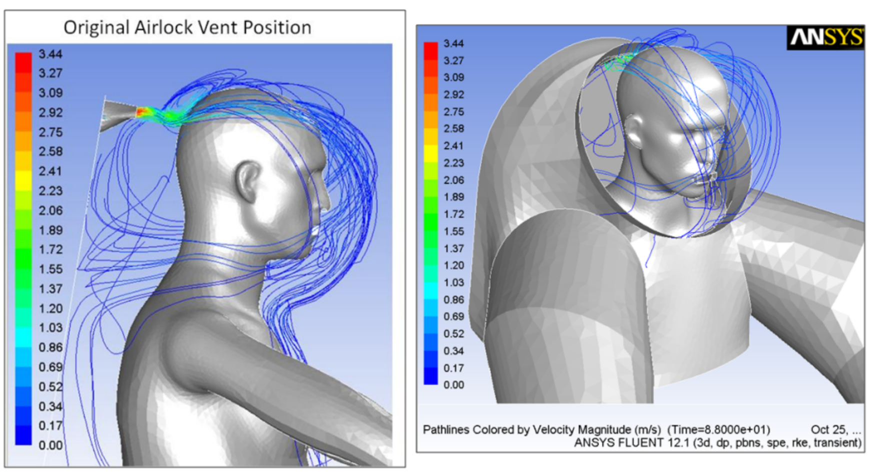

Figure 18. CFD flow patterns resulting from Z1 suit evaluation.

Preliminary model results were compared to Z1 test results (Fig. 19). The CFD model consistently predicted CO_2 inhale values within the Z1 test data scattered values. It is recommended that this correlation be revisited since the breathing patterns used in this investigation have since been updated in the model. Effects of the facial mask used during testing have not been evaluated with model.

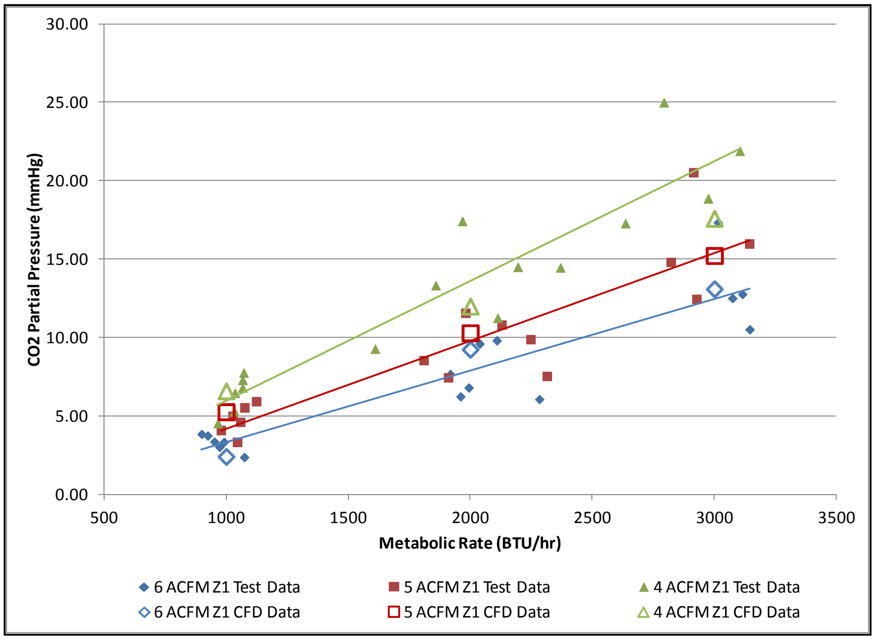

Figure 19. Preliminary CFD results compared to Z1 test results.

C. Z2 Suit Ventilation Duct Computational Fluid Dynamics Evaluations

A CFD analysis was also performed to aid in the design of a ventilation inlet design for the Z2 suit that would improve CO_2 washout. Ducting configurations evaluated are shown in Figs. 20-25. As mentioned earlier, historically, emphasis for adequate CO_2 washout has been placed on minimizing inlet CO_2 concentration and/or adjusting volumetric flow (more flow usually results in better washout). These approaches result in a sizing trade analysis between the sizing of a given CO_2 scrubbing technology and the sizing of a fan/power design that would provide adequate ventilation. The goal with this analysis was to design a ventilation delivery configuration that would improve CO_2 washout, which could potentially relax the demand on a CO_2 scrubbing technology and air delivery system.

The following assumptions were made for the case matrix:

- Metabolic Rate: 2000 BTU/hr
- 19 psia operating pressure
- Ventilation Flow Rate: 6 ACFM
- Inlet ventilation gas stream was composed of O_2 and N_2 (no H_2O vapor or CO_2).
- Airlock ventilation duct configuration supplies airflow
- Exit locations located at the wrists and waist of the spacesuit fluid domain
- Initial cases assumed 50/50 mouth/nose flow split
- 100% mouth flow cases were also evaluated

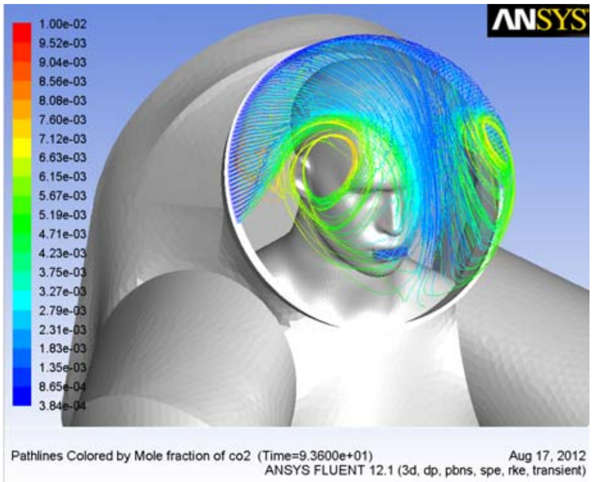

Figure 20: CFG A - "All Vents Open."

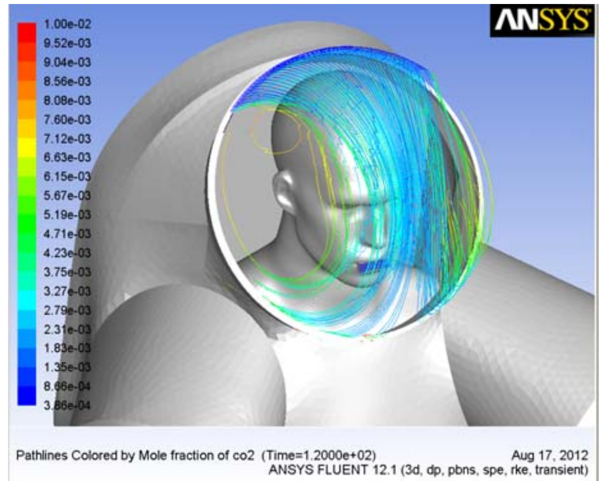

Figure 21: CFG B - “Y” + "Center Configuration."

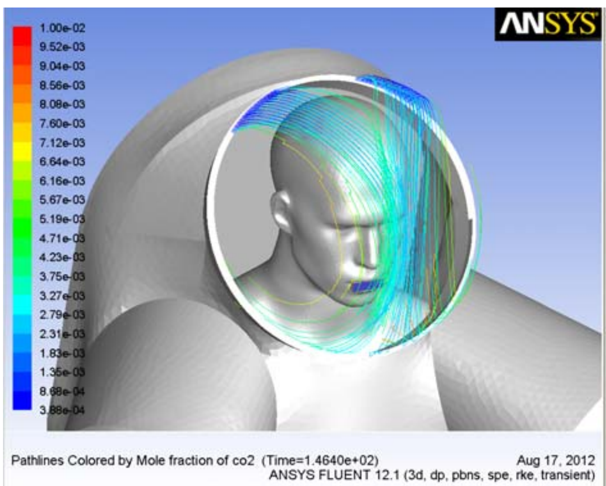

Figure 22: CFG C - “Y Configuration”

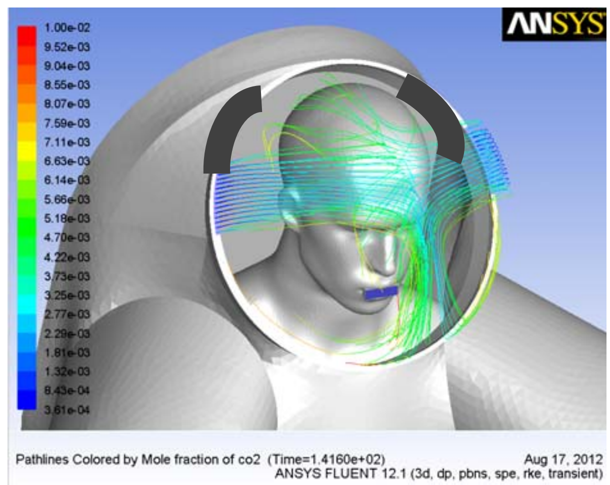

Figure 23: CFG D - "Y + Ear Configuration"

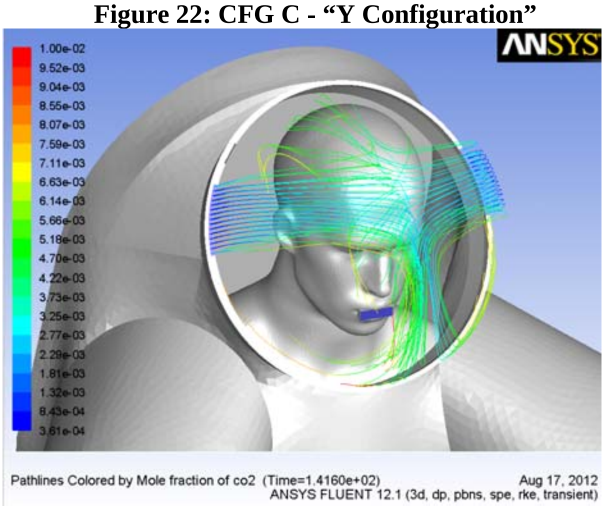

Figure 24: CFG F - “Ear + Center Configuration.”

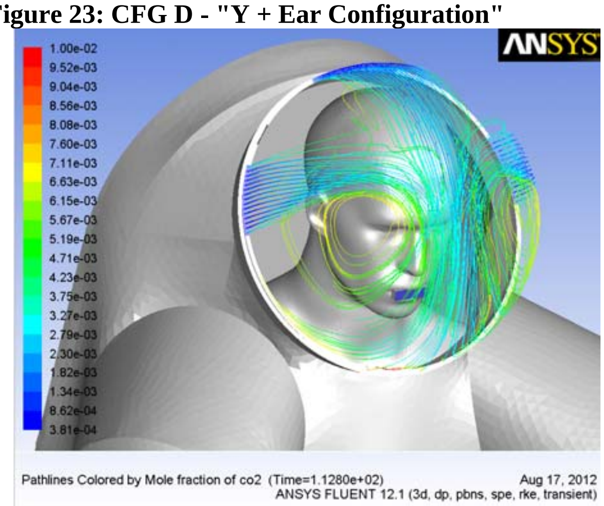

Figure 25: CFG E - "Ear Configuration."

Results from these cases are summarized in Table 1. Initial cases assumed a 50/50 mouth/nose flow split. Literature survey of prior human testing efforts indicated that a 50/50 mouth/nose split is a good fit for 2000 BTU/hr metabolic rate. The 100% mouth flow cases were added since the worst-case nose/mouth split is assumed to be 100% flow through mouth. This is because any nasal flow should help direct flow downward (aiding the CO_2 washout function). The CFD results showed higher CO_2 levels for the 100% mouth flow cases. Testing and CFD analysis of the Z1 ventilation duct showed that it provided a level of adequate CO_2 washout. However, there has been little investigation into the optimization of ventilation inlet design, both experimentally and numerically. In addition, CFD analysis has shown that the ventilation delivered by current Z1 inlet duct geometry is sensitive to the interaction with the head of suit-occupied human (Fig. 26).

Table 1. Summary Inhaled CO_2 Levels from Z2 Suit CFD Investigation

Average Inhale CO_2 Levels (mmHg)

Z1 Suit Cases 2000 BTU/hr Metabolic Rate and 6 ACFM Flow Rate	Mouth/Nose Flow Split	
	50/50	100/0
Original Inlet Duct	4.0	6.4
Y-adapter	6.0	
Y-adapter + midsection	7.2	
Ear	5.4	
Ear + midsection	4.5	6.7
Ear directed + midsection	5.4	
All vents opened	4.7	

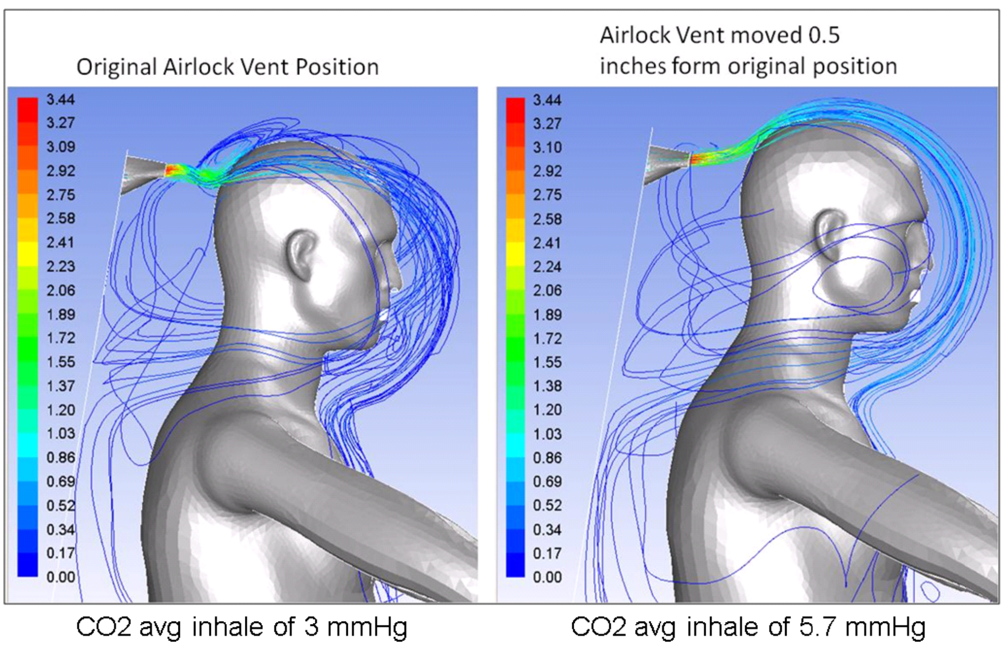

Figure 26. Sensitivity of flow patterns and CO_2 levels to head/inlet duct position.

Results of the Z2 ducting evaluation indicated that the Z1-type inlet helmet duct as configured in the baseline Z1 CFD model performs well compared to other configurations. A more robust duct configuration is recommended for future suit/helmet designs due to position sensitivities of the Z1 inlet duct design. The current Z1-type duct has some CO_2 washout risk associated with head position within helmet. A design that achieves efficient CO_2 washout and is fairly insensitive to head position should be investigated.

VI. Summary and Recommendations

CO_2 washout testing and CFD assessments have been and are continuing to be performed to aid in the AEMU development efforts. Human testing as well as SMTP testing are planned to be performed in 2013 and 2014 at JSC. Prior investigations have shown that helmet and ducting configurations can change the effectiveness of CO_2 washout performance. Human testing can be supplemented with SMTP testing to reduce total costs and to provide a stable repeatable configuration to provide a better basis for CFD model correlation efforts. The potential benefits from optimizing CO_2 washout performance include:

- Reduced PLSS/spacesuit ventilation flow rate requirements that could reduce power and fan performance requirements
- Reduced efficiency requirements for the PLSS CO_2 removal unit (RCA)
- More robust helmet/ducting designs that are less sensitive to head position, head size, hair/COMCAP configurations.

It is recommended that these investigations continue in order to quantify the risks associated with variations in crew member sizes and positions and to optimize ducting into and out of the helmet/spacesuit. A few configurations have been investigated, but many potential configurations exist that may provide better CO_2 washout performance for the AEMU and future spacesuits. Parameters that should continue to be investigated are:

- Breathing patterns (flow rates and frequencies)
- Mouth/nose flow split
- Variations in head sizes and shapes including hair impacts
- Head orientation within the helmet (height in the suit/turned head variations)
- COMCAP configurations
- Helmet ducting inlet and outlet locations
- Helmet ventilation flow rate variations
- Helmet inlet CO_2 levels
- Helmet design (shape)
- Metabolic rate variations

In summary, evaluations being conducted at JSC show that CO_2 washout may be sensitive to helmet and head configurations. Plans are in place to perform further testing with humans and with the SMTA to provide insight into CO_2 washout variables and to provide guidance for AEMU. These efforts are targeted to provide robust, safe, and efficient spacesuit designs.

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